

initial abundance, which is assumed to be entirely in the atmosphere, the model calculates the annually averaged temperature of the equatorial region and the polar region, and the planetwide mean. This calculation is based on the model of Gierasch and Toon [3], which we have modified to include a greenhouse effect. CO₂ is then weathered out of the atmosphere using the temperature and pressure-dependent parameterization of Pollack et al. [1] and McKay and Davis [4]. What remains in the atmosphere is then partitioned between the regolith and caps assuming the regolith can hold 300 mbar at present conditions (215 K, 7 mbar). The model then repeats these steps at 90-m.y. intervals, increasing the solar luminosity linearly to its present value.

Thus far we have obtained results for the case where CO₂ condensation in the atmosphere is not a limiting factor. The results fall into two categories: initial inventories above 1 bar and initial inventories below 1 bar. For initial inventories above 1 bar, CO₂ is immediately partitioned between the atmosphere and regolith with the latter taking up almost 800 mbar of CO₂. The rest remains in the atmosphere and is weathered out at a rate proportional to atmospheric pressure. Eventually, the atmospheric pressure becomes low enough (~100 mbar) that heat transport into the polar regions is no longer able to prevent polar caps from forming. At that point, the climate system collapses: atmospheric pressure drops catastrophically (to several millibars), huge polar caps form (~500 mbar), and the regolith gives up its CO₂ and equilibrates to about 300 mbar. The higher the initial pressure, the later in time this event occurs. For a 5-bar initial abundance the collapse occurs at 2 b.y.; for a 1-bar initial abundance the collapse occurs much earlier at around 700 m.y. For the remainder of the simulation, the caps slowly give up their CO₂ to the regolith and atmosphere, but they never disappear.

For initial inventories less than 1 bar, the evolution scenario is different. In these cases, polar caps form immediately since there is not enough greenhouse warming to prevent CO₂ from going into the regolith and thereby reducing the atmospheric pressure to levels where caps can form. In a sense, these simulations begin with a collapsed climate system. As the Sun brightens and temperatures warm, the caps shrink, giving up their CO₂ to the atmosphere, regolith, and rock reservoirs. Interestingly, these low initial abundance simulations suggest that the (permanent) polar caps are on the verge of disappearing at the present time.

While the results obtained thus far are intriguing, we cannot favor or rule out any particular scenario. However, it is clear that the evolution of the martian atmosphere may not have been monotonic in time, and that this result is directly attributable to the formation of polar caps. As was pointed out by Leighton and Murray [5] in 1966, once permanent polar caps form on Mars, their heat balance determines the surface pressure.

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THE POLAR LAYERED DEPOSITS ON MARS: INFERENCES FROM THERMAL INERTIA MODELING AND GEOLOGIC STUDIES. K. E. Herkenhoff, Geology and Planetology Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109, USA.

It is widely believed that the martian polar layered deposits record climate variations over at least the last 10-100 m.y. [1-8], but the details of the processes involved and their relative roles in layer formation and evolution remain obscure [9]. A common presumption among Mars researchers is that the layered deposits are the result of variations in the proportions of dust and water ice deposited over many climate cycles [3-5], but their composition is poorly constrained [10]. The polar layered deposits appear to be the source of dark, saltating material that has been distributed over the surface of Mars [11], but the mechanisms by which this material is incorporated and eroded from the layered deposits are unknown. These mechanisms must be understood before the processes that formed and modified the layered deposits can be inferred and related to martian climate changes.

Calculations of the stability of water ice in the polar regions of Mars [5,12] indicate that ice is not currently stable at the surface of the layered deposits. The present water-ice sublimation rate is high enough to erode the entire thickness of the deposits in about a million years. This result suggests that sublimation of water ice from the layered deposits results in concentration of nonvolatile material at the surface of the deposits. Such a surface layer would insulate underlying water ice from further sublimation, stabilizing the layered deposits against rapid erosion. The low albedo of the layered deposits does not necessarily indicate that an insulating dust layer is present, as the observed albedo only constrains the fraction of dust at the surface to be greater than 0.1% by mass if mixed with water-ice grains that have radii of 0.1 mm or larger [13]. The existence of a surface layer is more strongly supported by the low apparent thermal inertia of the surface of the south polar layered deposits [14]. However, a similar mapping study of the north polar region indicates that water ice is present near the surface of the north polar layered deposits and sublimating into the atmosphere [15]. Hence, it appears that while the present erosion rate of the south polar layered deposits is low, the north polar layered deposits (at least in some areas) are currently being eroded by ice sublimation. These inferences have important implications for the present water budget on Mars, and for the recent climate history of the planet.

The color and albedo of the layered deposits suggest that bright, red dust is the major nonvolatile component of the deposits. I have constructed a new Viking Orbiter 2 color mosaic of part of the south polar region, taken during orbit 358, using controlled images provided by T. Becker of the U.S. Geological Survey in Flagstaff. Analysis of this color mosaic indicates that a bright, red unit extends beyond the layered deposits, supporting my previous interpretation of this unit as mantling dust [16,17]. This result also supports the inference that the layered deposits contain both bright and dark materials in addition to water ice. The differences in albedo and color between mantling dust and exposures of layered deposits and the association of dark saltating material indicates that there is at least a minor component of dark material in the deposits [11,16]. If the dark material is composed of solid sand-sized grains, poleward circulation is required to transport the sand (by saltation) into the layered deposits [18]. Saltating sand would eject dust into suspension, hindering co-deposition of sand and dust. However, sand may have saltated over ice-cemented dust toward the poles at some previous time when winds blew onto the polar caps. In this case, the dark sand must have formed layers or lenses less than a few meters in size, or they would be visible in high-resolution Viking Orbiter images. Alternatively, dark dust (rather than sand) may be intimately mixed with bright dust in the layered deposits.

How can dark dust in the layered deposits form the dunes observed in the polar regions? Sublimation of dust/ice mixtures has been shown to result in the formation of filamentary sublimation residue (FSR) particles of various sizes [19]. Such particles can saltate along the martian surface, and may therefore create dunes [20,21]. In order to form saltating material that is at least three times darker (in red light) than the bright dust that mantles much of Mars, dark dust grains must preferentially form FSR particles. Magnetic dust grains would be expected to form FSR more easily than nonmagnetic dust, and are probably much darker. Experimental formation of FSR with magnetic material has not been attempted, and should be the subject of future research.

There is direct evidence for 1–7% magnetic material (magnetite or maghemite) in the surface fines at the Viking lander sites [22]. In addition, analysis of Viking lander sky brightness data indicates that suspended dust over the landing sites contains about 1% opaque phase, perhaps of the same composition as the magnetic material on the surface [22,23]. Within the uncertainties in these measurements, the percentages of magnetic material given above are identical to the volume of dark dune deposits in the polar regions expressed as a percentage of the estimated volume of eroded layered deposits [18,24]. This comparison indicates that the presence of magnetic dust in the layered deposits is likely, and that formation of dunes from dark FSR particles is plausible. Eventual destruction of the particles could allow recycling of the dark dust into the layered deposits via atmospheric sus-

pension. Under the assumption that FSR can be formed by sublimation of mixtures of water ice and magnetic dust, the thermal properties of this material have been estimated and compared with observational data, as detailed below.

A recent study using Viking IRTM observations of an area completely covered by dunes within the north polar erg [24] shows that the dunes have thermal inertias of less than $100 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$ [15]. Previous interpretations of martian thermal inertia data in terms of particle sizes have utilized the relationship between these quantities presented by Kieffer et al. [25], which is based primarily upon measurements of the thermal properties of quartz sands [26]. The low albedos of martian dunes are inconsistent with a siliceous composition, so basalt grains and magnetite FSR are considered here. The thermal conductivities of the materials considered here are only weakly dependent on temperature between 200 and 300 K, so values measured near 300 K have been used in all cases.

The thermal conductivity of basaltic sands is about $1.2 \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1}$ (~40%) less than that of pure quartz sands of the same size (~100 μm). If the polar dunes are composed purely of basaltic grains, their effective particle size is no greater than about 50 μm (40% porosity). Particles in this size range will be transported by atmospheric suspension [27], and are therefore not likely to form dunes. Hence, low-inertia materials that are capable of saltation must be examined as possible dune-forming materials on Mars. The thermal properties of FSR particles are therefore estimated below.

The density of magnetite is 5200 kg m^{-3} , almost twice that of quartz (2650 kg m^{-3}) or basalt ($2680\text{--}2830 \text{ kg m}^{-3}$). The specific heat of magnetite is $544 \text{ J kg}^{-1} \text{ K}^{-1}$ at 220 K [28], only slightly less than the specific heat of various silicates [29]. The porosity of clay FSR formed in laboratory experiments is 99% [19]. Magnetite FSR would therefore have a bulk density of only 52 kg m^{-3} . The thermal conductivity of porous clay at 313 K, 740 torr ranges from 0.477 to $2.05 \text{ W m}^{-1} \text{ K}^{-1}$, depending on water content [28]. The lowest value is identical to that of clay FSR [19]. When this dry clay was placed in a high vacuum, its thermal conductivity decreased only 7%. Therefore, the conductivity of clay FSR at 6 mbar is probably no greater than $0.47 \text{ W m}^{-1} \text{ K}^{-1}$. The thermal conductivity of clay minerals is probably similar to that of most silicates, about 2.8 times less than the conductivity of magnetite. Hence, magnetite FSR should have a thermal conductivity of $1.2 \text{ W m}^{-1} \text{ K}^{-1}$ or less, implying a thermal inertia of no more than $187 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$. The thermal inertia of ensembles of FSR particles may be lower still, and is compatible with the north polar erg thermal inertias derived from Viking data.

In summary, weathering of the martian layered deposits by sublimation of water ice can account for the thermal inertias, water vapor abundances, and geologic relationships observed in the martian polar regions. The nonvolatile component of

the layered deposits appears to consist mainly of bright red dust, with small amounts of dark dust. Dark dust, perhaps similar to the magnetic material found at the Viking Lander sites, may preferentially form filamentary residue particles upon weathering of the deposits. Once eroded, these particles may saltate to form the dark dunes found in both polar regions. This scenario for the origin and evolution of the dark material within the polar layered deposits is consistent with the available imaging and thermal data. Further experimental measurements of the thermophysical properties of magnetite and maghemite under martian conditions are needed to better test this hypothesis.

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THE MARS WATER CYCLE AT OTHER EPOCHS: RECENT HISTORY OF THE POLAR CAPS AND LAYERED TERRAIN. Bruce M. Jakosky, Bradley G. Henderson, and Michael T. Mellon, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder CO 80309-0392, USA.

The martian polar caps and layered terrain presumably evolve by the deposition and removal of small amounts of water and dust each year; the current cap attributes therefore

represent the incremental transport during a single year as integrated over long periods of time. We have investigated the role of condensation and sublimation of water ice in this process by examining the seasonal water cycle during the last 10^7 yr. In our model, axial obliquity, eccentricity, and L_s of perihelion vary according to dynamical models. At each epoch we calculate the seasonal variations in temperature at the two poles, keeping track of the seasonal CO_2 cap and the summertime sublimation of water vapor into the atmosphere; net exchange of water between the two caps is calculated based on the difference in the summertime sublimation between the two caps (or on the sublimation from one cap if the other is covered with CO_2 frost all year). Despite the simple nature of our model and the tremendous complexity of the martian climate system, our results suggest two significant conclusions: (1) Only a relatively small amount of water vapor actually cycles between the poles on these timescales, such that it is to some extent the same water molecules moving back and forth between the two caps. (2) The difference in elevation between the two caps results in different seasonal behavior, such that there is a net transport of water from south to north averaged over long timescales. These results can help explain (1) the apparent inconsistency between the timescales inferred for layer formation and the much older crater retention age of the cap and (2) the difference in sizes of the two residual caps, with the south being smaller than the north.

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POSSIBLE RECENT AND ANCIENT GLACIAL ICE FLOW IN THE SOUTH POLAR REGION OF MARS.

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Martian polar science began almost as soon as small telescopes were trained on the planet. The seasonal expansion and contraction of the polar caps and their high albedos led most astronomers to think that water ice is the dominant constituent. In 1911 Lowell [1] perceived a bluish band around the retreating edge of the polar caps, and he interpreted it as water from melting polar ice and seasonal snow. An alternative idea in Lowell's time was that the polar caps consist of frozen carbonic acid. Lowell rejected the carbonic acid hypothesis primarily on account of his blue band. To complete his refutation, Lowell pointed out that carbonic acid would sublimate rather than melt at confining pressures near and below one bar; hence, carbonic acid could not account for the blue watery band. Some of the many ironies in comparing Lowell's theories with today's knowledge are that we now recognize that (1) sublimation is mainly responsible for the growth and contraction of Mars' polar caps, (2) carbon dioxide is a major component of the southern polar cap, and (3) Lowell's blue band was probably seasonal dust and/or clouds.